CURRENT STATUS OF PAL-XFEL*

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Abstract

The PAL-XFEL project aims to produce 0.1 nm coherent X-ray laser to photon beam users. In order to produce such photons, there are 10 GeV electron linac based on S-band normal conducting accelerating structures and a 150 m long out-vacuum undulator system. The project was already started in April 2011, and the 1.1 km long building is expected to be completed by December 2014. The injector test facility (ITF) which is for a test of the first 139 MeV section of the main linac has been installed and is in normal operation at the extension of the PLS linac building. In this paper, we introduce the project in general, a brief summary of site preparation and building construction, beam test results of ITF, and test results of subsystems produced by domestic manufacturers

PROJECT OVERVIEW

The Pohang Accelerator Laboratory X-ray Free-Electron Laser (PAL-XFEL) project was started in 2011. This project aims at the generation of X-ray FEL radiation in a range of 0.1 to 10 nm for users [1, 2]. The machine consists of a 10 GeV electron linac and five undulator beamlines (see Fig. 1). The linac is based on the normal-conducting S-band technology, which has been used for the 3 GeV full energy injector linac of PLS-II, the 3rd generation light source at PAL, over 20 years [3]. As Phase-1 of PAL-XFEL, one hard X-ray undulator beamline with two experiment stations and one soft X-ray undulator beamline with one experiment station are under preparation. Both undulator systems are variable-gap, out-vacuum type.

The building is under construction and to be ready by December 2014. Accelerator components will be installed from January 2015 over the year. The layout of the PAL-XFEL linear accelerator and undulator lines is shown in Fig. 2. Experiment beamline components will be installed during the same period. The machine is capable of 60 Hz operation with a single bunch initially. Main parameters of the first Phase of PAL-XFEL are summarized in Table 1. Upgrade to a 120 Hz repetition rate as well as two micro-bunches is foreseen as the next phase. A fast kicker to divide electron pulses into the two undulator beamlines is considered as future upgrade.

Accelerator commissioning will be started in winter 2015. Beam commissioning will be carried out at a repetition rate of 10 Hz for the first year of operation mainly due to the operation budget. First FEL generation is foreseen in early summer 2016. First experiment using FEL beam will be possible in summer 2016.

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Table 1: Main Parameters of PAL-XFEL Phase I

FEL wavelength	
hard X-ray	0.1 - 0.06 nm
soft X-ray	3 - 1 nm
Electron beam energy	
hard X-ray	4 - 10 GeV
soft X-ray	3.15 GeV
Bunch charge	200 pC
Repetition rate	60 Hz
# of bunches per RF pulse	1
Gun type	S-band photocathode gun
Linac type	S-band normal conducting
Linac hall length	716 m
Beam transport line	57 m
Number of beamline	
hard X-ray	1
soft X-ray	1
Undulator type	out-vacuum
Undulator hall length	
hard X-ray	246 m
soft X-ray	125 m
Number of experiment station	
hard X-ray	2
soft X-ray	1
XFEL beamline hall length	
hard X-ray	60 m
soft X-ray	74 m
Total building length	1110 m

BUILDING CONSTRUCTION

The building construction was started in autumn 2012. The 1.1 km long new machine is being built on the northern hill of the PAL campus (see Fig. 3). Soil on the site was removed until 56 m altitude from the sea level. Most of the building lies on the sedimentary bedrock. For the area where the bedrock does not reach the altitude, soft X-ray experiment hall area, soil was removed and the empty volume was replace with hard concrete.

2 m thick concrete floor was constructed for the linac and undulator tunnel area. Linac tunnel wall and roof is 2 m thick for radiation safety. Possible radiation effect was studied and checked that the residential area is safe from the radiation produced by PAL-XFEL [4]. Construction of the Iron frames for the outside building is recently finished. Flat panels are being attached to the frame. Six utility buildings are under construction along the southern side of the main building. The building construction including utilities will be ready by December 2014.

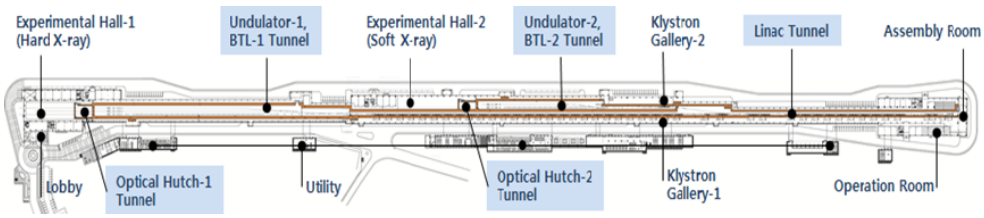

Figure 1: Layout of the PAL-XFEL buildings. The beam direction is from the right to the left.

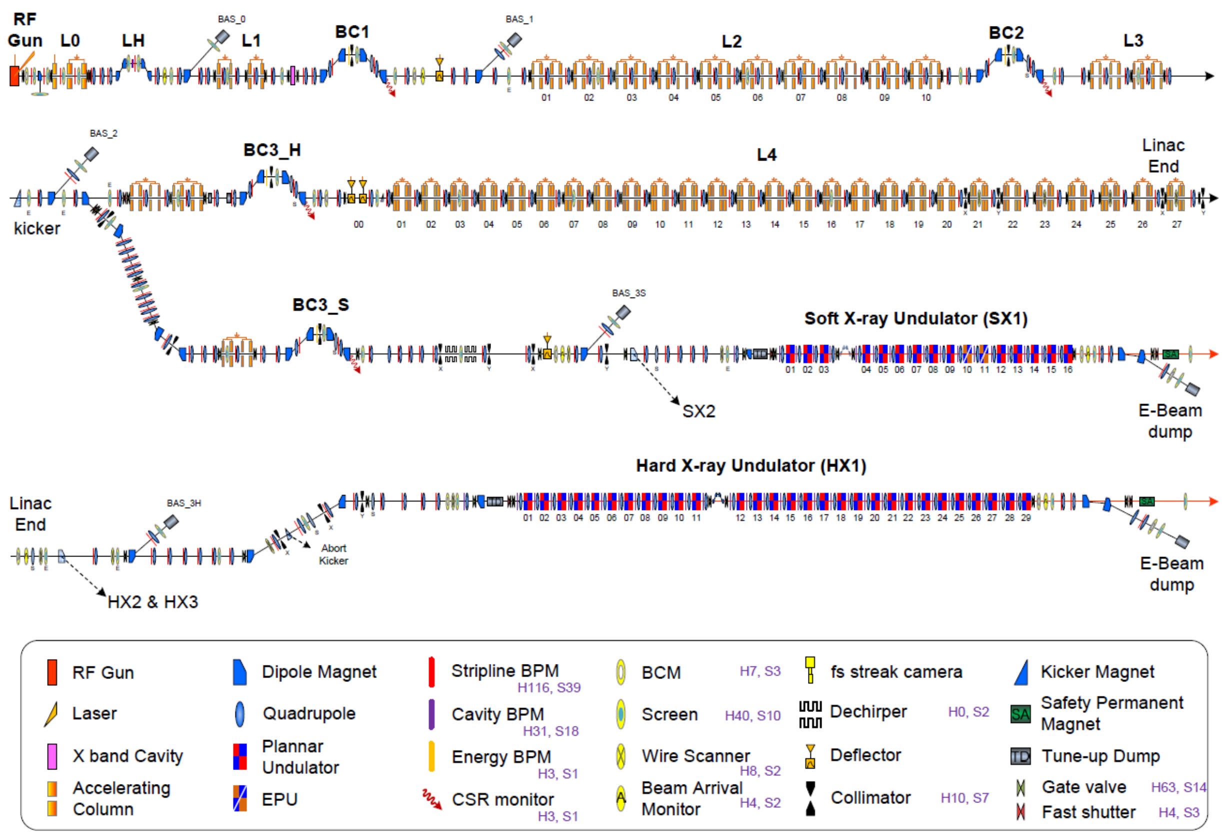

Figure 2: Layout of the PAL-XFEL linac and undulator.

Figure 3: Aerial view of the PAL-XFEL construction site on 24 July 2014.

INJECTOR

The injector consists of an S-band (2.856 GHz) photocathode gun, three 3 m long S-band (2.856 GHz) traveling wave structures, and focusing solenoids. The peak accelerating field at the cathode is 120 MV/m and the beam energy at the gun exit is 5.7 MeV. After further acceleration through three S-band structures, the beam becomes over 130 MeV.

Beam commissioning is ongoing at the Injector Test Facility (ITF) since December 2012 [5]. This facility was constructed at the extended building of the full energy injection linac of PLS-II. Figure 4 shows the view of the ITF tunnel and gallery. The roof of the tunnel is removed for the component installation in the photograph. During the operation, the roof is covered for radiation safety.

Transverse emittance was routinely measured. The value at 0.2 nC bunch charge is between 0.45 and over 1.0 depending on the machine parameters [6]. For each measurement point, gun solenoid field was optimized for best emittance compensation condition. For the emittance measurements, various drive laser size and length, RF phases of the gun and first accelerating structure, RF amplitude of the gun, and current of the accelerating structure solenoid were used.

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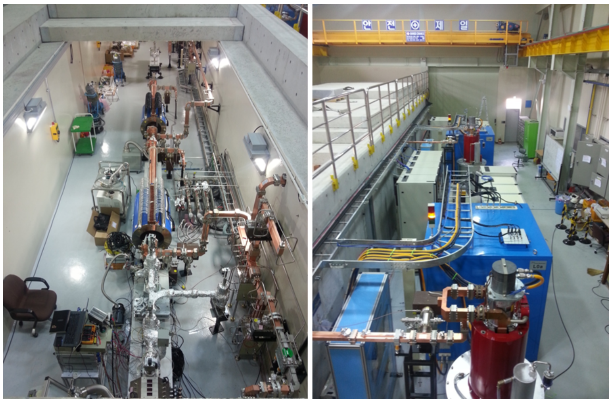

Figure 4: Injector Test Facility (ITF) of PAL-XFEL. The accelerator components are installed in the tunnel (left). The RF systems, magnet power supplies other facility control systems are installed in the gallery (right).

Various experiments using electron beams at ITF were carried out. The international collaboration with SLAC and BNL confirmed the performance of a dechirper system in summer 2013 [7]. Beam based stripline beam position monitor (BPM) test was done for a few different type of BPM controllers. Stability test using an optical timing system

The baseline gun has been developed at PAL, which consists of 1.6 cells and a high power RF coupler on the side of the second cell [8]. Two RF input holes are made with mirror symmetry and two additional pumping holes reduce the high-order modes of the RF field [9].

The first gun used for ITF was produced in 2011 for the test at the Gun Test Facility (GTF), which was located in the underground ATF area. The gun was used for the first beam generation at ITF before the PAL-XFEL prototype gun, named Gun1-0, was produced in spring 2013. Gun1-0 was an improved one in terms of brazing and tuning. The gun was used for the ITF beam operation from summer 2013 to summer 2014. In September 2014, another gun, named Gun1-1 (Fig. 5), will be tested at ITF. This gun will be used for PAL-XFEL beam commissioning.

The copper back plane of the gun cavity is used as photocathode. During the nominal operation, the quantum efficiency (QE) of the cathode is a few 10^{-5}. When laser cleaning was applied, the QE was recovered to 10^{-4} and

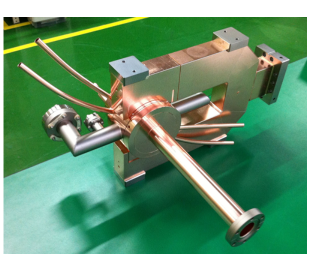

Figure 5: Gun to be used for PAL-XFEL commissioning, Gun1-1. Machining was done by a local company. Cleaning and vacuum brazing were carried out in PAL.

stayed for a few months. The drive laser system is a commercial regenerative amplifier from Coherent Inc. The center wavelength of the Ti:sapphire laser system is 770 nm. The wavelength is tripled for the beam generation at the gun.

RF LINAC

Normal-conducting constant-gradient 3 m long S-band traveling-wave structure is adopted for electron beam acceleration at the injector and main linac [10]. One RF station will feed four accelerating structure at the high energy part of the linac, e.g., after the first magnetic bunch compressor (BC1). SLAC energy doublers (SLEDs) will be used for doubling the peak power from klystrons. Since RF jitter affects the electron beam parameters more sensitively at the low energy part, every two structures before BC1 will be fed by one RF station and the first structure at the injector will have an RF station.

Two companies, Mitsubishi Heavy Industries in Japan and VITZROTECH in Korea, are manufacturing accelerating structures. High power test has been carried out at the Accelerator Test Facility (ATF) for the prototypes of the three suppliers (see Fig. 6) [10].

Figure 6: Accelerator column high power test setup at ATF.

High power modulator was developed by collaboration of PAL and two domestic companies, DAWONSYS and POSCO ICT. Stability requirement of voltage stability is 50 ppm for the RF phase stability of 0.03° in the S-band and 0.1° in the X-band. The prototypes made by both companies satisfied the requirement. R&D for high power RF source has been done at ATF (see Fig. 7). 51 modulators are being manufactured by the companies.

Low level RF (LLRF) modules consisting phase-amplitude-detector and phase-amplitude-controller were developed as collaboration of PAL and domestic companies, Mobiis and NEOLINX. Two companies demonstrated the stability requirement, 0.05% amplitude and 0.05° phase. An example of LLRF long term test is shown in Fig. 8. 55 LLRF modules for PAL-XFEL are under production by Mobiis. R&D on LLRS system is ongoing at ITF and ATF [11].

Two X-band klystrons, model XL4, and one 0.6 m linearizer cavity are being manufactured by SLAC. One X-band RF station will be used for linearizing the beam shape in longitudinal phase space and the other one will be a spare.

Figure 7: High power RF test setup at ATF.

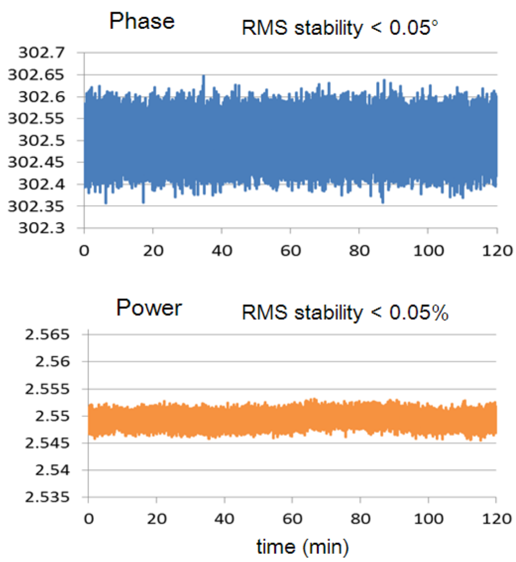

Figure 8: Low level RF test result for a long term, 2 hours.The stability requirement of PAL-XFEL LLRF system is satisfied.

UNDULATOR

The hard X-ray undulator beamline is located at the main linac end, where the maximum beam energy is 10 GeV. A SASE FEL radiation of 0.1 nm will be produced by 18 planar undulators. The undulators are 5 m long, variable gap and out-vacuum type [12]. The hard X-ray undulator hall is 246 m long; therefore some space is reserved for possible further installation for seeding schemes. Two more hard X-ray undulator beamlines will be added in the future.

The soft X-ray undulator beamline is branched from the main linac at the 3 GeV position. Six 5 m long planar undulators and two elliptically polarized undulators (APPLE-II type) will be installed for full polarization control. One more soft X-ray undulator beamline will be added in the future.

The gap is variable and controlled with 1 μm rms reproducibility. A prototype was produced and test in the Insertion Device Test Laboratory, located in the stock building (see Fig. 9) [13].

Two field measurement benches were manufactured by Bruker. The measurement bench was tested as in Fig. 10. The peak fields from five measurements are overlapped.

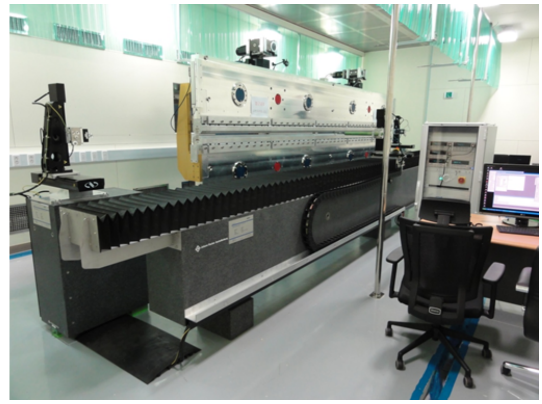

Figure 9: Insertion device test laboratory (top) and field measurement set-up of the undulator prototype (bottom).

Measured magnetic field errors are about ±1.0 G. Orbit error from the measurements is less than 1 μm [13].

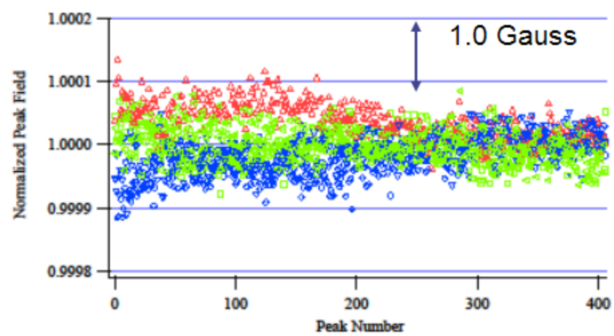

Figure 10: Field measurement test of the prototype undulator using the bench manufacture by Bruker.

Using the measurement bench and prototype undulator, gap reproducibility was tested. The reproducibility requirement better than 1 μm was satisfied [14] (Fig. 11).

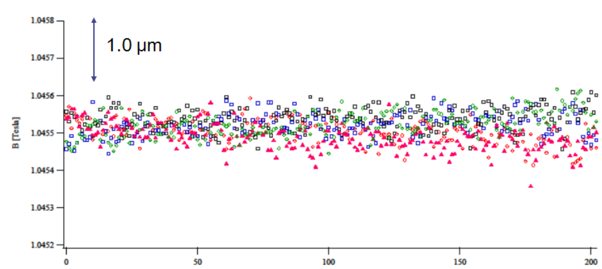

Figure 11: Insertion device test laboratory (top) and field measurement set-up of the undulator prototype (bottom).

When an electron beam passes though the long undulator chamber, the resistive wakefield affects the beam energy spread. A surface roughness less than 150 nm and an oxide layer thickness less than 5 nm are required in the PAL-XFEL undulator chamber. Prototypes of undulator chamber were manufactured (Fig. 12). The parameters of the prottotype chamber are summarized in Table 2.

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Figure 12: Insertion device test laboratory (top) and field measurement set-up of the undulator prototype (bottom).

Table 2: Undulator Chamber Prototype Parameters

Parameter	Value
Undulator Length	5 m
Undulator Period	24.4 mm
Undulator gap	7.2 mm
Material	A6063-T5/T6
Aperture, V × H	5.2 × 11 mm
Thickness	0.5±0.05 mm
Flatness	< 50
Clearness (pole to chamber)	0.5 mm

PHOTON BEAMLINES

Following the requests of Korean synchrotron radiation user societies, an X-ray pump-probe (HX-XPP) and a coherent X-ray imaging (HX-CXI) experiment stations at the hard X-ray beamline, and an X-ray pump-probe experiment station (SX-XPP) at the soft X-ray beamline are under preparation as Phase-I. Designs of the photon optics for the experiment stations are ready. Optics components are under preparation. Detector R&D, one of most critical issues in XFEL user beamline, is ongoing as collaboration with European XFEL.

SUMMARY

The PAL-XFEL building is under construction and to be ready by December 2014. Test facilities and laboratory for the core technology development and test have been built and are being operated. Prototype test of the RF and undulator systems was successful and manufacturing is ongoing for the final delivery in autumn 2015. Components installation in planned to be started in January 2015 and continued over the year. Beam commissioning will be started in January 2016 for first SASE FEL generation in late spring 2016. First FEL beam will be available for experiment in summer 2016.

REFERENCES

[1] J.-H. Han et al., "Status of the PAL-XFEL project," in *Proceedings of 3rd Int. Particle Accelerator Conf.*, New Orleans, 2012, p. 1735.

[2] H.-S. Kang et al., "Current status of PAL-XFEL project," in *Proceedings of 4th Int. Particle Accelerator Conf.*, Shanghai, 2013, p. 2074.

[3] S. H. Nam et al.,"Upgrade of Pohang Light Source (PLS-II) and challenge to PAL-XFEL," Synchrotron Radiation News 26, p.24 (2013).

[4] N.-S. Jung et al., "Design for Radiation Shielding of PAL-XFEL," presented at *12th Meeting of Task-Force on Shielding Aspects of Accelerators, Targets and Irradiation Facilities*, Fermi National Laboratory, 2014.

[5] S. J. Park et al., "Construction of injector test facility (ITF) for the PAL XFEL," in *Proceedings of 4th Int. Particle Accelerator Conf.*, Shanghai, 2013, p. 2220.

[6] J.-H. Han et al., "Beam operation of the PAL-XFEL Injector Test Facility," in *Proceedings of 36th Int. Free-Electron Laser Conf.*, Basel, 2014, WEB02.

[7] P. Emma et al., "Experimental demonstration of energy-chirp control in relativistic electron bunches using a corrugated pipe," Phys. Rev. Lett. 112, 034801 (2014).

[8] J. Hong et al., "Development of photocathode rf-gun at PAL," in *Proceedings of 35th Int. Free-Electron Laser Conf.*, New York, 2013, p. 279.

[9] M. S. Chae et al, "Emittance growth due to multipole transverse magnetic modes in an rf gun," Phys. Rev. ST Accel. Beams 14, 104203 (2011).

[10] H.-S. Lee et al., "PAL-XFEL accelerating structures," in *Proceedings of 4th Int. Particle Accelerator Conf.*, Shanghai, 2013, p. 2806.

[11] J. Hu et al., "Experimental test of the prototype LLRF systems for PAL-XFEL," in *Proceedings of 5th Int. Particle Accelerator Conf.*, Dresden, 2014, p. 2462.

[12] D. E. Kim et al., "First results of the PAL-XFEL prototype undulator measurements," in *Proceedings of 4th Int. Particle Accelerator Conf.*, Shanghai, 2013, p. 3561.

[13] K. H. Park et al., "Field measurement facility for PAL-XFEL undulators," in *Proceedings of 5th Int. Particle Accelerator Conf.*, Dresden, 2014, p. 2032.

[14] D. E. Kim et al., "Status of PAL-XFEL undulator program," in *Proceedings of 5th Int. Particle Accelerator Conf.*, Dresden, 2014, p. 2029.